

# FT 1030 HERA - DLTS

Basics Manual

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# Introduction

This part of the DLTS manuals should give an overview about the principles of the digital DLTS measurements and how the additional measurement features are meant to be used for getting exact and reliable results. Special applications will also be explained here. It can not and is not meant to give a complete, detailed basis about the theory of deep levels, surface states or Schottky and MOS diode theory. This can only be covered by science books and publications, for literature examples have a look in the Theory Manual. One of these books is:

SEMICONDUCTOR MATERIAL AND DEVICE CHARACTERIZATION,  
Second Edition, Dieter K. Schroder, Wiley-Interscience, John Wiley & Sons, Inc.,  
ISBN 0-471-24139-3

All evaluations of the measured data in our software are strictly based on fundamental theories and formulas. A short formula reference is given in the Theory part of the manuals and the appended publications.

The following will give an overview about the interaction between the DLTS software and the hardware with an explanation of all used measurement parameters and their effect on the measurements. Examples for special applications will also be given.  
The complete software will be described more in details in the Software Manual.

This manual is the 4. part of the main DLTS documentation set:

- 1) **Hardware manual H**
- 2) **Installation manual I**
- 3) **Software manual S**
- 4) **Basics manual B** (this manual)
- 5) **Theory manual T**

The Basics manual provides information how to make DLTS measurements and shows some special applications.

Reference to another chapter of this manual will be denoted only by this chapter, for example 1.1. If there is a reference to another manual the type of this manual will be additionally given, for example S3.1 for chapter 3.1 of the software manual. The equations, most abbreviated by 'equ.', refers to the Theory Manual.

# 1. Measurement Principles and Parameters

The DLTS Hardware measures Capacitance  $C$  and Current  $I$  of a sample (Schottky diode) as a function of the voltage  $V$  or time  $t$ . Only these two signals (the Constant Capacitance option gives a third one, the regulating Voltage) can be measured with the voltage or the time as the given variable. This gives 3 measurement modes and 6 measurement results:

1. Single value measurement:  
 **$C(V_r)$** : A capacitance measurement at 1 bias voltage value  $V_r$   
 **$I(V_r)$** : A current measurement at 1 bias voltage value  $V_r$
2. Voltage dependent measurements, static measurements:  
 **$C(V)$** : Same as in 1., but with automatic variation of the bias voltage of the sample. The result is a data array with measured capacitance and the corresponding voltages, a  $C(V)$  curve.  
 **$I(V)$** : Similar to the  $C(V)$ , the result is the  $I(V)$  curve.
3. Time dependent measurements, transient measurements:  
 **$C(t)$** : The capacitance (at a particular voltage  $V_r$  as in 1.) is measured as a function of time. The result is the capacitance transient  $C(t)$ .  
 **$I(t)$** : Similar to  $C(t)$ , but the bias current as the measured signal.

The voltage curves will be called  $C/V$  resp.  $I/V$  curves. The voltage in the equations will be denoted by a 'U' or a 'V', the reverse bias is  $U_R$  resp.  $V_r$ . So  $V$  and  $U$  means the same. In our manuals no difference will be done between both notifications.

In addition to the variables time and voltage, other parameters (e.g. the samples temperature) are not effecting the measurement, only the results and the evaluations.

In the following the explanations are reduced to the capacitance measurements, the current measurements are done in an analogue way. It should give an idea of how the interaction between the measurement software and the hardware is done and which kind of parameters effecting the measurements can be modified by the user.

## 1.1 Single value measurement

This measurement mode is used in the 'test for contact' routines C/V (I/V) and in combination with any transient measurement. The **measurement cycle** (for automatic range and amplification control) is as follows:

- A: If 'new sample' flag is off goto C:
- B: **New sample initialization**
  - Set Boonton meter to 'direct mode'
  - Set the Bias Voltage (BIAS/PULSE Source) to the defined value
  - Set Amplifier Input to Capacitance (if not already done)
  - Set Boonton meter range to 4
  - Set Amplification factor to 1
  - Set filter frequency to 20Hz (maybe changed, see measurement params)goto D
- C: **Continued measurement**
  - keep actual Boonton meter range
  - keep actual amplification factor
- D: **Start measurement**
- E: Read Transient Recorder output
- F: **Compare** output readings (in digits) with predefined reading window.  
(standard definition:  $300 < \text{reading digits} < 1300$ , see below)
  - if the reading is inside the window, goto END
  - if the reading is above the window goto H: After 3 tests goto END
- G: **Under range procedure**
  - Set Boonton meter range to 'actual - 1' range or if the 'range low limit' value for 'static measurements' has still been set, stay in the actual Boonton meter range
  - Check and optimize amplification factorgoto E:
- H: **Over range procedure**
  - Set Boonton meter range to 'actual + 1' range or if the 'range 4' has still been set, stay in the actual Boonton meter range
  - Check and optimize amplification factorgoto E:
- END: **Calculate** the capacitance using the output reading, the Boonton range setting and the amplification setting.

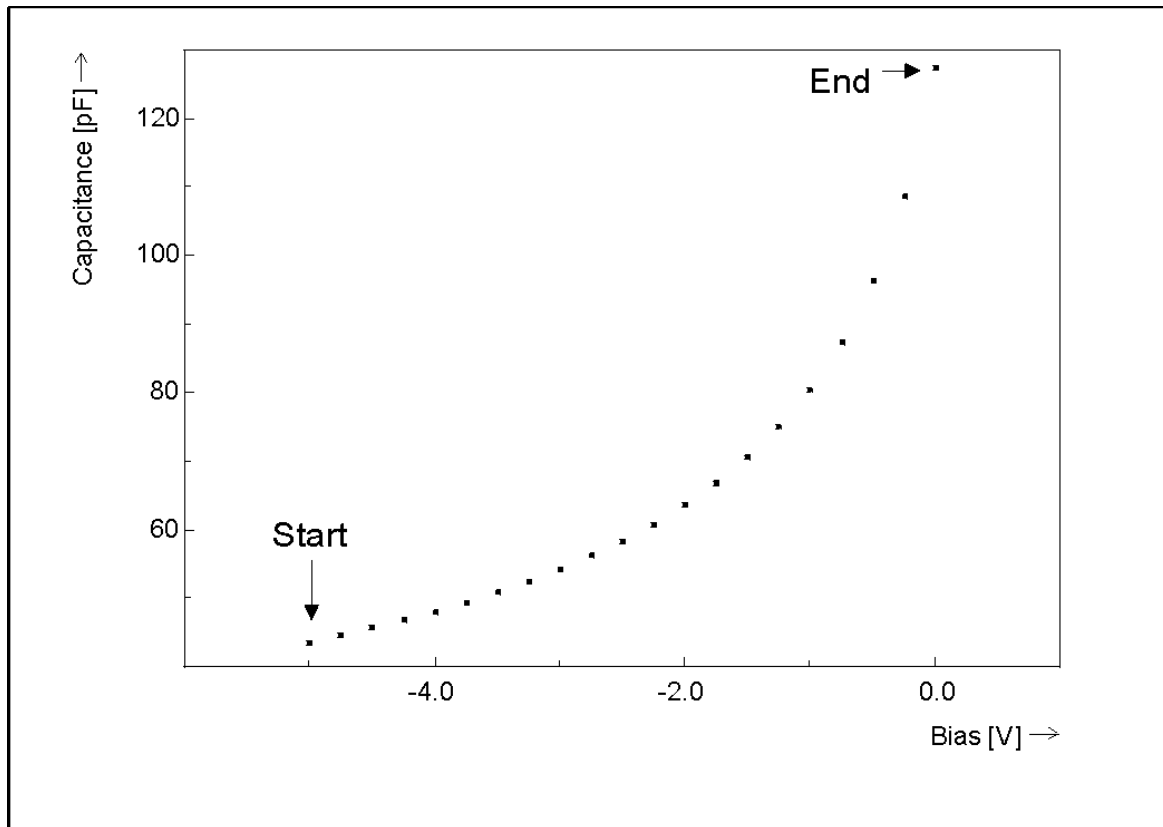
For manually controlled measurements (see below 'Input Hardware Parameter', automatic range and amplification control switched off, D: is changed to D: Set defined range to Boonton, set defined amplification factor and commands F: to H: are skipped.

The only measurement variable, the **BIAS Voltage**, is either defined in the static or transient input window (Reverse Bias Voltage) for the combined measurement with a transient measurement, or in the test of contact measurement input window (Reverse Bias and/or Pulse Voltage). These input windows are explained later.

## 1.2 Static measurements

'Static' in this case means, that the measurements are done slowly compared to any relaxation and emission processes of the sample (Schottky diode). The aim of these measurements are the I/V or C/V curves as given in equations 1.3 and 1.16 of the theoretical part.

A typical C/V curve of a Schottky diode is shown below. From the measurement point of view (evaluations etc. will be explained in the Software Manual), this curve is measured by



several 'single value' measurements (see above) under systematical variation of the Bias Voltage. The measurement limits(Start Voltage, End Voltage) and the number of point per curve has to be defined by the user using the following input window. This input window is always the same, independent from the main measurement module (available in: Static measurement, Isothermal measurement and Tempscan measurement as well as in the contact check measurement modules).

### C/V (I/V) parameter input window:

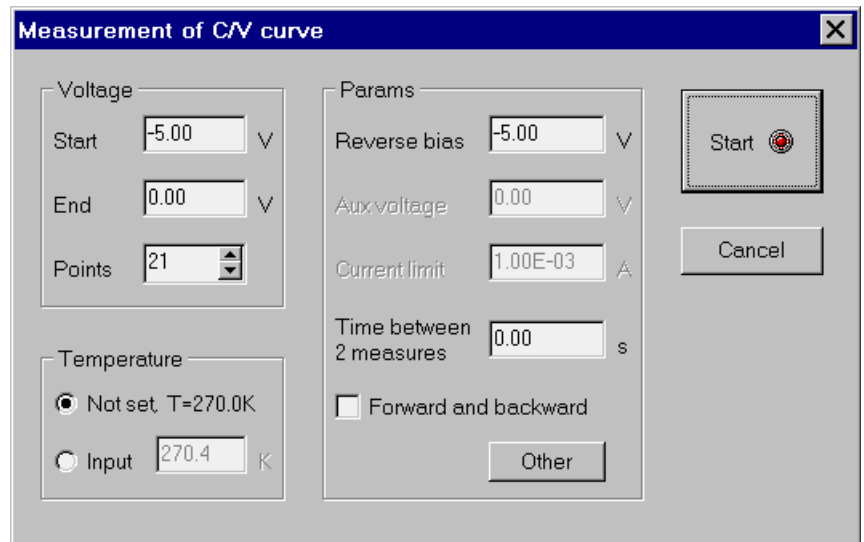
Following parameters and variable values can be defined

1. *The measurement variable*, the **Bias Voltage**, left top box of the input window:

The '**Start Voltage**' value (e.g. -5V), the '**End Voltage**' value (e.g. 0V) and the numbers of measured data **points** between these values can be defined. The measurement direction (high to low or low to high voltages) and the voltage range (+20V) for each input are normally not limited. Only on predefined (routine) measurement tasks the voltage range can be limited to the **reverse bias** range due to the doping type (**p**: **positive**, **n**: **negative voltage range**).

## 2. Temperature input box (left side bottom):

The measurement can be done at the actual temperature of the cryostat (not set) or at a definable one (input). If that flag is activated, the cryo get the command to set this temperature and after its stabilization, the C/V curve measurement starts automatically.

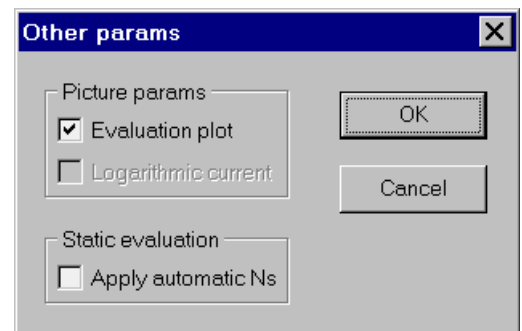


## 3. Parameter input box (right side) with additional parameters, not effecting the C/V curve measurement itself, can be defined here:

- Reverse Bias:** This voltage is set to the sample after the C/V curve measurement has been finished.
- Auxiliary Voltage:** This input is activated for FET samples, it defines a second voltage (Bias/Pulse board, 'Aux' output) that can be used as a Drain-Source voltage.
- Time between 2 measurements:** An additional waiting time between two C/V data point can be defined to make the measurement slower.
- Forward and backward:** Enables a two direction measurement (Start to end and end to start voltage) to check hysteresis effects.

**Other Parameters** in this input window only defines the diagram appearing directly after the measurement.

'Start' starts the measurement cycle.



## C/V (IV) measurement cycle:

- A: **Check Temperature**  
If temperature = not set goto D:  
Set defined Temperature Tset to cryostat controller
- B: Read Temperature  
if measured temperature T = Tset goto C:  
goto B:
- C: **Wait for stable Temperature**
- D: **Start C/V (I/V)**  
Measure temperature  
Calculate bias voltage increment  $U_i [(U_{start}-U_{end})/no. \text{ of points}]$   
Set Bias voltage to Start Voltage  $U_{start}$

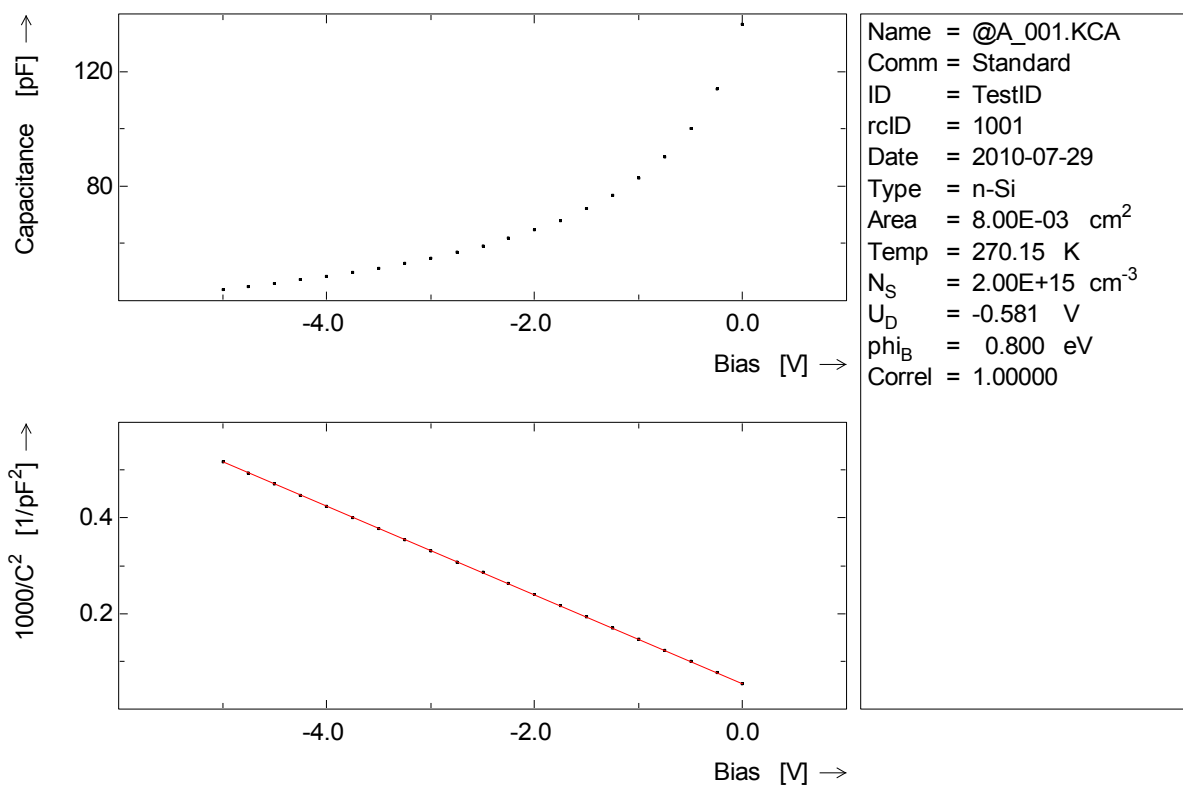


```

E:      Goto single measurement cycle
        store measured capacitance C and the actual bias voltage U in C/V array
        plot measured data
        Set  $U = U_{start} + U_i$ 
        if  $U > U_{end}$  goto END
        goto E
END:    measure temperature
        calculate temperature average  $[(T_{start} - T_{end})/2]$ 
        Display measured C/V array and defined evaluation
Stop

```

A **typical plot** after the measurement is shown below.



The upper plot shows the measured data, the second one (if required) gives the evaluated data (equation 1.4 and 1.5), with the calculated data ( $N_s$ ,  $U_D$ ,  $\phi_B$ ) and some sample parameters on the right. 'Correl' means the correlation factor for the linear regression line used for the evaluation. It is quality factor for the linearity of the  $1/C^2$  versus  $V$  plot. Some more plots and evaluations are possible with this data and available in the 'static' measurement module (see software manual), but only the shallow doping  $N_s$  is necessary for DLTS measurements and should be transferred into the sample parameter array (manually or automatically, see software manual 'sample parameters'). For I/V measurements all procedures are similar. The used equations are 1.15 and 1.16.

### 1.3 Transient measurements

The transient measurements (time dependent capacitance or current measurement) is in opposite to the measurements explained above a non-equilibrium measurement. This non-equilibrium behavior of the sample capacitance is due to 'slow' emission processes that are caused by impurities creating an energetic active level in the band gap of a semiconductor so called trap levels. The sample is driven into this non-equilibrium behavior by changing the bias voltage:

- A: The trap levels are under constant bias conditions (Schottky diode, defined reverse bias voltage  $U_R$ ) partly filled (see fig. 1.1a, theoretic part of the manuals) due to the actual Fermi level in the semiconductor bulk.
- B: Changing the bias voltage at the sample Schottky diode to nearly 'flat band' conditions (fig. 1.1b of Theory Manual), nearly all traps are filled, occupied with majorities, in a very fast capture process. This condition we call pulse condition defined by a pulse voltage  $U_P$ .
- C: Switching back to reverse bias conditions (fig. 1.1c), the trap level is over occupied compared to the actual Fermi level. The trapped majorities (electrons: n-type material, holes: p-type material) are now emitted into the main band (conduction band for n-type, valance band for p-type material) and can be observed by measuring the capacitance of the Schottky diode (equation 1.24) as a function of time.

This measurement gives the so called capacitance transient. The Schockley Read Hall (SRH) model for the emission process of a **single** trap level gives following fundamental sentences:

1. The capacitance change (transient) is exponential in time. (equ. 1.24).
2. The time constant  $t_e$  of the transient is exponentially changing with the temperature.
3. The time constant  $t_e$  of the transient is exponentially changing with the energy  $E_C - E_T$  (enthalpy) of the trap level (equ. 1.49).
4. The transient amplitude is directly proportion to the trap concentration  $N_T$ , but the reverse bias capacitance  $C_R$  and the shallow doping  $N_S$  are necessary for it's calculation (equ. 1.25, 1.36).

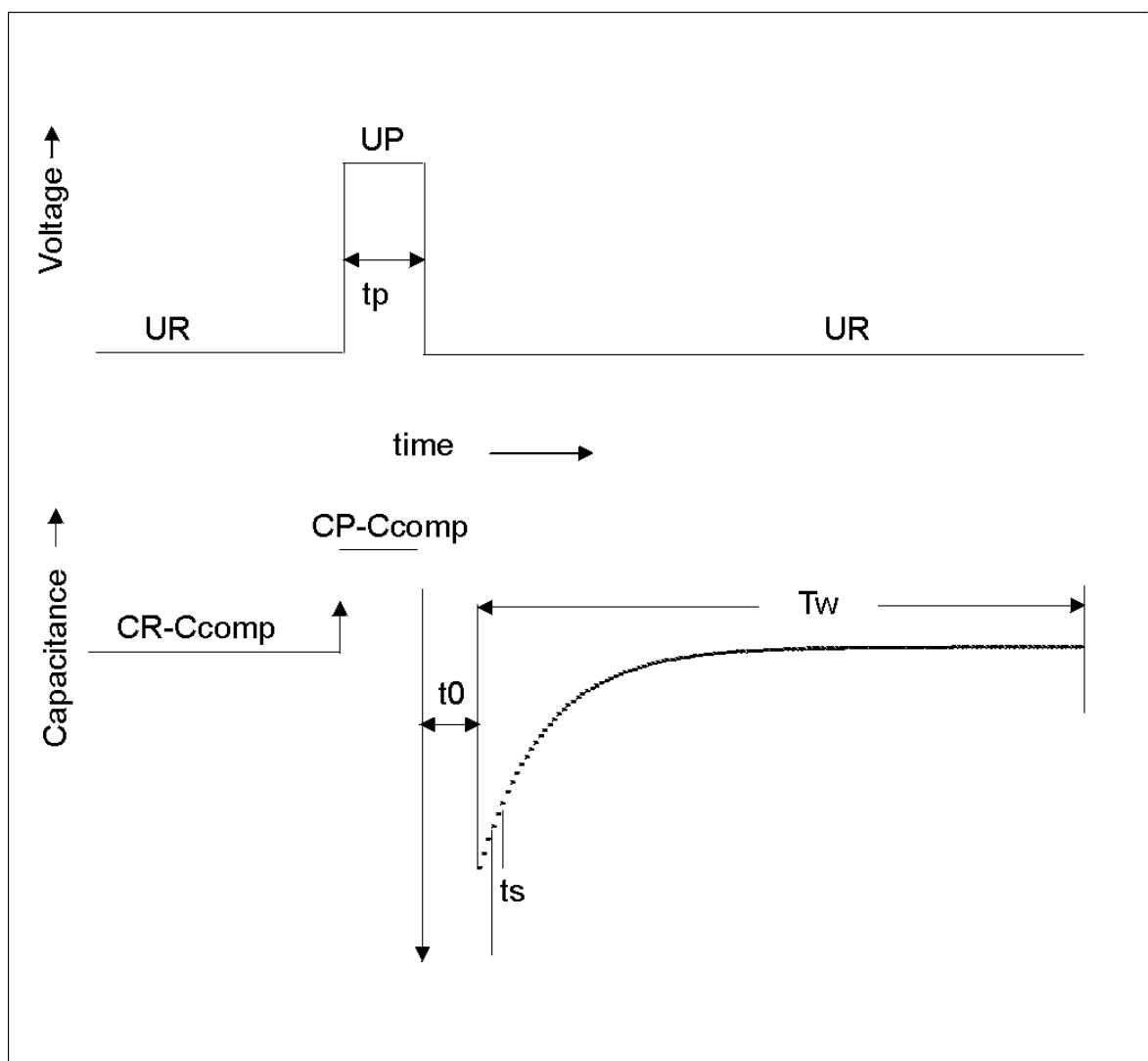
The final result of the DLTS measurements are: The trap energy  $E_C - E_T$  and the trap concentration  $N_T$  as accurate and sensitive as possible. For that the time constant has to be determined as a function of the temperature, and the transient amplitude has to be measured. The base for both is a capacitance transient measurement optimized for capacitance changes and not for the absolute capacitance. This leads to the compensated measurement mode for the capacitance transients.

### Compensated measurement mode for capacitance transients:

The diagram below shows the voltage supplied to the sample (top) and the (compensated) capacitance signal from the sample.

The measurements cycle starts (left side) setting the defined reverse bias voltage of the sample  $U_R$  (condition A) the sample capacitance is now compensated using the compensation capacitance connected to the differential input of the Boonton meter. The reading of the capacitance meter (in a more sensitive range than in direct mode) is around 0. Then 'flat band' conditions (B) are supplied to the sample for a short time by setting the bias voltage to the defined pulse voltage  $U_P$  for the pulse time  $t_p$  to fill all traps. The capacitance meter is staying during the pulse in the sensitive range and therefore it's driven very hard into over range conditions.

After the pulse, reverse bias voltage  $U_R$  is supplied to the sample again to measure the emission capacitance transient (C).



Before the measurement itself is started, the system has to wait a time  $t_0$  for the Boonton meter to recover from the overload. Then the transient recorder is started automatically measuring and storing the capacitance value any time  $t_s$  till the defined numbers of points has been reached.

To enhance the signal to noise ratio (means also to become more sensitive) transients can be added and averaged automatically till a minimum measurement time  $t_M$  has been reached. The minimum measurement time affects not the period width and the pulse width. Therefore the real measurement time, called total measurement time  $t_{Mt}$  can be longer. The variables  $t_0$ ,  $t_d$  and  $t_{Mt}$  are calculated by the software. User definable variables are  $T_w$ ,  $N$  and  $t_M$ .

The **variables** in detail:

- $U_R$ : Reverse Bias Voltage (input parameter)
- $U_P$ : Pulse Voltage (input parameter)
- $t_P$ : Pulse Width (input parameter)
- $t_0$ : Recovery time (calculated)  
 $t_0 = t_{Boonton} + 6 \cdot t_d$ , where  $t_{Boonton}$  is a definable time (measurement parameters) to allow the Boonton meter to recover from overload (input variable)
- $T_w$ : Period width (total measurement time for one transient) (input variable)
- $N$ : Numbers of measured transient points (input variable, predefined to 512)
- $t_d$ : Sampling interval (calculated),  $t_d = T_w / N$ , called  $t_s$  in the picture above
- $t_M$ : Minimum measurement time (input variable)
- $t_{Mt}$ : Total measurement time (calculated)
- $N_a$ : Numbers of averages per transient measurement (calculated),  $N_a = t_M / T_w$

We distinguish between measurement variables and measurement parameters. The variables ( $T_w$ ,  $t_M$ ) define the measurement itself (time axis, y-axis) the measurement parameters define the physical conditions of the sample before the transient measurement. This different definitions seem on the first view not very logical, because variables and parameters do both effect the result. But from the measurement point of view, each measured transient is a single independent measurement and does not 'see' anything from the former transient or will effect the next transient. DLTS or ITS measurements are now done under systematic variation of one (or several) physical parameter (e.g. the temperature for a tempscan) and the results of the transient measurements have to be combined with each other. This combination of several transients with different measurement **parameters** ( $T, U_R, U_P, \dots$ ) is only possible if the measurement **variables** ( $T_w, t_0$ , not necessarily  $t_{Mt}$ ) are exactly the same.

The software will deny parametrized evaluations (like subtractions of transients or temp-scans with different parameters) if the measurement variables are not identical.

## Transient parameter input window:

The input window for the transient measurement variables and parameters is not the same for all measurement tasks. It differs due to the parameters that shall be varied during parametrized transient measurements (e.g. transients measured under temperature variation for a tempscan). But for the single transient measurement task (transients, measure, single transient) as an example all input parameters and variables can be explained.

As all input windows, this is also divided into several input boxes:

Period width/time: Input box for the variables  
Bias/pulse : Input box for pulse and reverse bias conditions and additional parameters (Params)  
Temperature: Input box defining the measurement temperature  
Start: Starts the measurement  
Cancel: Cancels the input window (all inputs are lost)

**Period width/time input box**, the measurement variables have to be defined here:

**Input:** Defines which variables can be modified:  
**Tw (normal):** The period width  $T_w$  and the minimum measurement time  $t_{Mt}$  can be defined (should be used as a standard).  
**Tw, N:** In addition to the standard inputs, also the numbers of points per transient can be defined.  
**Tw, N, t0:** In addition to the above variables an additional time for the recovery time  $t_0$  can be defined.

**Period width:** The period width  $T_w$  can be defined here. This is the main and dominating variable of the transient measurement. If, due to the hardware specifications, between points and period width, this input is kept as defined and the numbers of transient points is changed to fit the specifications. E.g.  $T_w = 1\text{ms}$  and  $N = 1024$  conflicts with the fastest sampling interval  $t_d = 2\text{ms}$  therefore  $N$  is reduced to  $N = 512$  or  $256$ .

**Minimum measure time tM:** Defines the total time of the measurement tMt. It includes the period width Tw, the delay time after pulse t0, the pulse width tp and the number of averages Na. The software calculates from tM the number of averages by  $Na = tM / (Tw + t0 + tP)$ . Na will be rounded, the minimum is 1. So  $tMt = Na * (Tw + t0 + tP)$ , where Na is an integer number equal or bigger 1. The standard value for tM is 1 second, which gives quite a good signal to noise ratio. The S/N ratio becomes better or worse with the square root of the numbers of averages. E.g. to reduce the S/N ratio by a factor of 10, the measurement time has to be enlarged to 100s. 100s or even 1000s can be used for very very sensitive measurements, but the temperature has to be also very stable during the measurement time.

**Additional delay:** An additional time t0Add can be defined. It is used to enlarge the recovery time t0. t0 is calculated then by  $t0 = t_{Boonton} + 6 * td + t0Add$ .

**Points:** Defines the numbers of points per measured transient. Normally the standard definition of 512 points is best. Only for background measurements (transient measurements without pulse, for noise detection) we suggest 1024 points. For period width scans (Isothermal transient measurements under variation of the period width) we suggest 64 points.

**Note:** t0 is a measurement variable. That means, transients or parametrized transient measurements with different t0 can not be combined with each other.

When should additional delay be used? It should be used if measured transient show at the beginning a not monotone behavior or a small maximum. This behavior is due to the pulse recovery of the capacitance meter. The recovery time of the Boonton meter  $t_{Boonton}$  (typical 150 - 250 ms) is valid for an adapted (50 to 100Ohm) circuit. Real circuits including the sample capacitance and serial resistance as well as the parallel resistance (leakage current) can be in some cases the reason for a very much longer recovery behavior. Especially high leakage currents (>10 to 100mA) or better the current densities or high serial (bulk) resistances can easily cause recovery time in milliseconds. In these cases, to enable correct transient measurements and evaluations this additional delay time should be used. It should be defined as short as possible, and (e.g. for tempscans) under respect, that sample conditions may change with temperature.

The **Bias/Pulse input box** contains the transient measurement parameters:

**Reverse Bias Voltage  $U_R$ , Pulse Voltage  $U_p$ , Pulse Width  $t_p$**  and for FET measurements an **Auxiliary Voltage  $U_{aux}$**  resp. UDS can be defined here.

The decision what values shall be used for the parameters above should be done under respect to the physical parameters of the semiconductor material and to the electrical behavior of the Schottky diode (p/n diode) of the sample. Physically  $U_p - U_R$  defines the information depth, the volume in the bulk material where the traps are reloaded and from where the emission is detected (equ. 1.25 ff). For a correct and reliable concentration analysis  $U_p - U_R$  should be as large as possible, and  $U_p$  should be as close to the surface (close to 0V, but not 0 itself, use -0.1V for n-type) as possible. In this case also the DLTS approximation (equ. 1.31) can be used. The absolute accuracy of the results is of course also dependent of the exact knowledge of the shallow doping  $N_s$  and the contact area. If only a small voltage difference can be used, it's absolute necessary for reliable results to use the exact formula for the calculation of the trap concentration  $N_{Ts}$  (equ. 1.34).

The values for  $U_p - U_R$  are normally limited by the  $C(V)$  and  $I(V)$  behavior of the sample:

- The leakage current at  $U_R$  should not be higher than app. 10 nA (sometimes even 100 nA can be used, but then the transient has to be checked).
- The capacitance difference  $C(U_p) - C(U_R)$  has to be smaller than app. 20 times the full scale reading of the desired measurement range of the Boonton meter (range low limit for transients, see measurement params).  
(e.g. Range 1:  $C(U_p) - C(U_R) < 60 \text{ pF}$ , Range 2:  $C(U_p) - C(U_R) < 600 \text{ pF}$ )

The limits above are not meant to be absolute limits. It guaranties for nearly all samples correct measurements. Most samples can also be measured outside these limits, but the results have to be checked carefully.

### Other Parameter input window:

The 'Params' button leads to an input window for additional pulse and measurement parameters. Two input boxes define the pulse mode, the start of the transient recorder, and the values for an optional second pulse.

### **Pulse parameter input box:**

'Pulse mode' opens a list of available pulse modes. The list is enhanced if optional pulse sources (optical interface and fast pulse interface with an external pulse generator) are installed:

- without pulse:** Transient measurements are done without a pulse. The inputs for the pulse are ignored. This pulse mode is meant to use for noise checks at measurement conditions (sample attached,  $U_R$  set).
- normal:** Pulse mode as explained above.
- double pulse:** Selecting this pulse mode the inputs for the additional pulse above is enabled. The transient measurement is done that way, that the first pulse voltage (so called injection pulse voltage  $U_i$ ) for the time  $t_{pi}$  is supplied, and then the standard pulse voltage  $U_p$ . There is no time or different voltage between these ones.

'Start of measurement' opens a list that defines the start of the transient recorder:

- normal:** Start the transient recorder directly after the pulse as explained above.
- at pulse,  $t_p = T_w$ :** Starts the transient recorder with the pulse. The pulse width is set to the value of period width. The capacitance is measured as the function of time during the pulse. Especially using an optical excitation this mode is very useful to see the capacitance change during the pulse.
- at pulse,  $t_p$  input:** Starts the transient recorder again with the pulse. But in this mode the period width  $T_w$  and the pulse width  $t_p$  can be defined independently from each other. The capacitance is now measured during and partly (as defined) after the pulse. It enables the measurement of the recovery behavior of the circuit including the sample. Because the capacitance variation is quite high during this kind of measurement the 'range low limit for transients' have to be increased to 3 or 4.

### Transient measurement cycle:

- A: **Check Temperature**  
If temperature = not set goto D:  
Set defined Temperature Tset to cryostat controller
- B: Read Temperature  
if measured temperature T = Tset goto C:  
goto B:
- C: **Wait for stable Temperature**
- D: **Start transient measurement**  
Measure temperature  
Set Bias voltage to sample  
**gosub to compensation cycle**  
If 'compensation error' goto END  
goto **single value measurement C:**  
(returned value =  $C_{\text{offset}} = C_R(\text{sample}) - C_{\text{comp}}$ )  
calculate  $C_R = C_{\text{comp}} + C_{\text{offset}}$   
set static measurement mode to I (current measurement)  
goto **single value measurement C:**  
(returned value =  $I_R$ , the leakage current at rev. bias voltage)  
Set Pulse voltage and width values to Bias source  
calculate and set delay time to TRC  
calculate add set filter frequency to filter (due to td)  
Set CPU to idle and start TRC (delete TRC memory)
- E: **Start pulse and data collecting sequence**  
Trigger pulse source  
collect C(t) data (digits)  
add C(t) data to memory data  
if no. of C(t) transients < defined no. of averages goto E:
- END: Restart CPU  
calculate averaged transient: digits = memory digits/no. of averages  
transfer data (digits) to main computer  
calculate C(t) (pF) = C(t) (digits) \* range \* Amp. factor  
measure temperature  
calculate temperature average [(Tstart-Tend)/2]  
Display measured C(t) array and defined evaluation



### Compensation cycle:

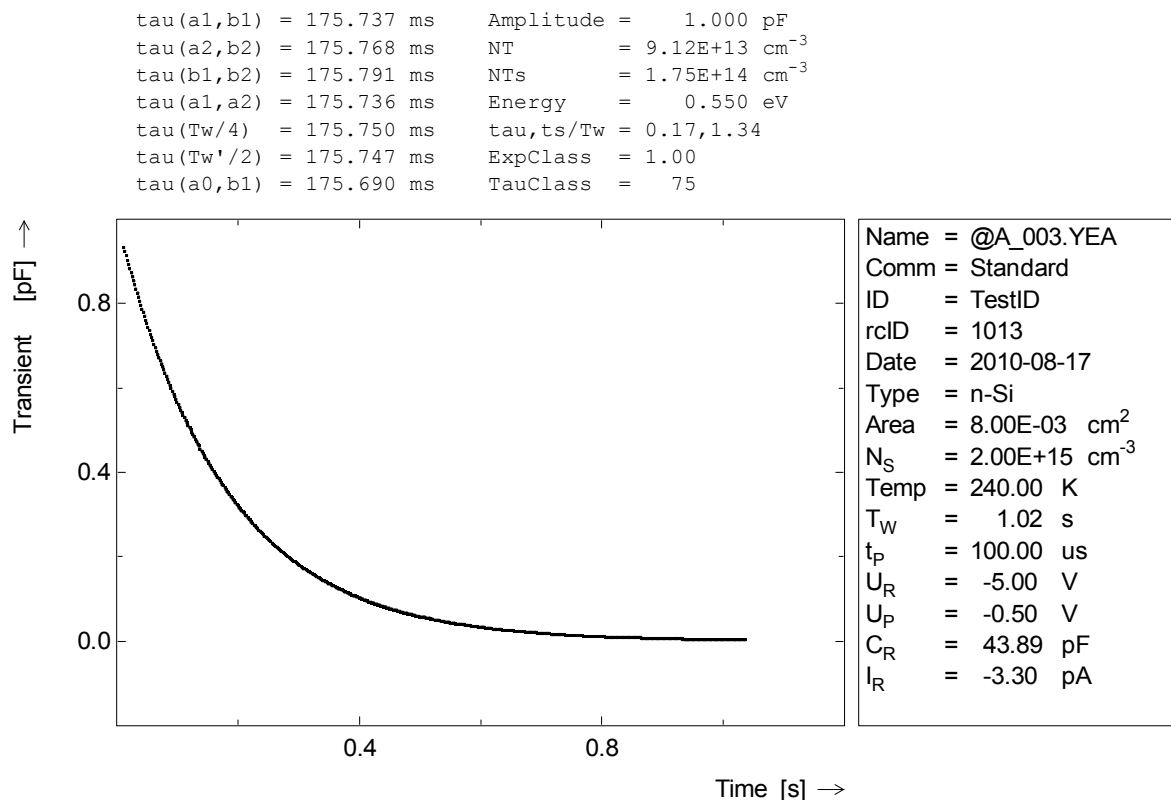
A: **Check compensation**  
If actual measurement mode = direct measurement goto C:  
measure Boonton output voltage  $V_{\text{Boonton}}$   
at actual range, actual  $C_{\text{comp}}$  and actual amplification  
if output  $V < 0,5 \text{ V}$  goto F:  
B: **Modify  $C_{\text{comp}}$**  slightly (variable capacitor only)  
if no. of loops  $< 5$ : goto A:  
C: **New compensation**  
set measurement mode to compensated measurement  
set Boonton range to 4  
set  $C_{\text{comp}} = 0$   
read Boonton output  
calculate sample capacitance  $CR = C_{\text{Boonton}} \cdot \text{Range} \cdot \text{Amplification}$   
set  $C_{\text{comp}}$  to CR  
D: read Boonton output  
if  $V_{\text{Boonton}} < 0,5 \text{ V}$  goto E  
calculate  $C_{\text{offset}} = CR - C_{\text{comp}}$   
set  $C_{\text{comp}} = C_{\text{comp}} + C_{\text{offset}}$   
if no. of loops  $< 5$  goto D:  
set error flag to compensation error: goto END  
E: next range  
If Boonton range = lowest range for transients: goto F:  
set Boonton range = Boonton range - 1  
goto D:  
F: **Voltage compensation**  
END: If error flag = 0: goto display  
If loop  $< 5$ : goto C:

Note: if (maximum digits - minimum digits)  $> 1300$  set over range flag  
if (maximum digits - minimum digits)  $< 300$  set under range flag  
if under or over range calculate and set new amplification:  
if amplification factor has been changed 5 times in a row: goto break  
goto E:  
over range gives ADC error: goto END  
under range skips the Amplification check and continues

### Display:

For a single transient measurement the transient and relevant evaluated data is shown.  
For parametrized measurements normally only the transient itself is shown in a special window.

The plot below displays all capacitance / time data as measured. The box on the right gives a list of important sample data, measurement parameters and variables and the results of the static (single value) measurements. On the top the results of the direct evaluation of this transient is shown.



### Measurement and sample parameters:

Comm:	Comment. <b>Can</b> be defined in the 'Sample Parameter' input window.
ID:	Sample identification. Any letters or numbers (up to 10) can be used. It's also defined in 'Sample Parameters'. If it is not defined 'ID' is used.
Date:	Date of the measurement (computer date is taken).
Type:	n or p type. <b>Has to be</b> defined in 'Sample Parameter'.
Area:	Schottky (or P/N) diode contact area. For correct evaluations it is absolute necessary to define the correct area.
Ns:	Shallow doping. This value is used for all evaluations. It can either be defined in 'Sample Parameter' or directly after a C/V measurement and 1/C <sup>2</sup> versus V evaluation. The result of the evaluation can directly transferred into the sample parameter set.
Temp:	Measurement temperature
T <sub>W</sub> :	Period width
t <sub>P</sub> :	Pulse width
U <sub>R</sub> :	Reverse Bias Voltage
U <sub>P</sub> :	Pulse Voltage
C <sub>R</sub> :	Capacitance at reverse bias voltage
I <sub>R</sub> :	Leakage current at reverse bias voltage

## Evaluation values:

For any measured transients up to 30 different values using as many different correlation functions (see Theory chap. 4) are calculated. Some of these correspond to the Fourier coefficients  $a_1$ ,  $a_2$ ,  $b_1$ ,  $b_2$  etc. (Theory chapter 3). These one are now used to calculate the time constant of the transient by the 'direct' evaluation (Theory chap. 3.3).

The following explains the result list of the **direct evaluation**:

- tau(a1,b1):** Time constant calculated by  $a_1$  and  $b_1$ , will be used as  $\tau$ .
- tau(a2,b2):** Time constant calculated by  $a_2$  and  $b_2$ .
- tau(b1,b2):** Time constant calculated by  $b_1$  and  $b_2$ .
- tau(a1,a2):** Time constant calculated by  $a_1$  and  $a_2$ .
- tau(Tw/4):** =tau(a1L,b1L), time constant calculated at the first quarter of  $T_w$ .
- tau(Tw'/2):** =tau(a1M,b1M), calculated by tau(a1,b1) with  $T_w'=T_w/2$ ,  $t_0'=t_0+T_w/16$ .
- tau(a0,b1):** Time constant calculated by  $a_0$  and  $b_1$ .
- Amplitude:** Amplitude of the transient.
- NT:** Trap concentration, standard approximation.  $N_s$  is necessary for this value.
- NTs:** Trap concentration, calculated with the space charge region.
- Energy:** Calculated from  $\tau$  and from in the sample parameters defined capture cross section.
- tau/Tw:** Time constant divided period width.
- ts/Tw:**  $t_s$  is the time when the transient has decreased to the ADC (Analog Digital Converter) resolution.
- ExpClass:**  $a_1/a_2 * b_2/b_1$ , is 1 for a single exponential transient.
- TauClass:** Classification of the  $\tau$  calculation, where
  - 1 – 6** : Error during measurement
  - 7 – 9** : Transient is not taken into account
  - 10** : No evaluation was done
  - 11-29** : No signal suitable for evaluation
  - 30-39** : Coefficient ratios do not correspond to the assumed transient type or shape
  - 40-49** : There is an evaluable signal but the shape is not assignable
  - 50-59** : Probably the transient is of the assumed type
  - 60-75** : The transient is of the assumed type

## 1.4 Tips

### 1) Bias and pulse for Schottky diodes:

The reverse bias direction will be in the negative voltage direction for n-type samples, in positive voltages for p-type sample. Select UR so that you have a wide space charge region and the leakage current is not high, typically it should be smaller than 1 $\mu$ A. UP should be selected a little bit smaller than zero volt. Don't use forward voltages or UP=0. Typical voltages for n-type samples are UR=-7V until -5V and UP=-0.5V. For standard samples select 100 $\mu$ s as pulse width. This time is enough to fill the most traps. Longer pulse widths can yield to longer recovery times. Only in special cases at extreme small capture cross section it can be necessary to use longer pulse widths.

### 2) Selection of period widths in the tempscan:

We prefer definite period widths (Tw). This have the advantage that files are comparable and combinable (subtraction, addition) if they have the same period width. So if you make 2 measurements with same Tw on 2 samples then the peaks of the temperature curves appear on the same temperature position if the levels in the 2 samples are identical.

The following lists our **favored period widths**, in brackets are the alternative values:

**A) 1 Tw:** N=512, Tw=204.8 ms

**B) 2 Tw's:** N=512, Tw1=20.48ms (5.12ms), Tw2=2.048s (0.512s)

**C) 2 HERA:** N=128, Tw1=48ms, Tw2=480ms

**D) 3 HERA:** N=128, Tw1=19.2ms (4.8ms), Tw2=192ms (48ms), Tw3=1.92s (0.48s)

For a good Arrhenius-plot with a wide temperature range you need 2 different Tw's, an overlap is not necessary. The HERA transient evaluation needs 2 or better 3 Tw's with a small overlap.

You get more information in chapter S3.4.1.1.4 of the Software Manual.

### 2) Averages versus period width:

The signal to noise ratio (SNR) and so sensitivity will only be determined by the total measurement time  $N_a \cdot T_w$ , where  $N_a$  is the number of averages. The SNR is proportional to the square root of  $N_a \cdot T_w$ . The frequency of the anti-aliasing filter and of the first Fourier coefficient is lower at a bigger Tw. So Tw=1s with  $N_a=1$  gives the same SNR as Tw=1ms with  $N_a=1000$ . But this is the theory and assumes a white noise, it don't take into account 50Hz noise of the power supply or drifts based on a not stable temperature. A period width which cuts the 50Hz peaks can be better than averages, on the other hand drifts yield to problems at long Tw's.

### 4) Selection of temperature ramp mode in the tempscan:

You should use in most cases the linear computer ramp. But an additional temperature stability check procedure with long waiting times is necessary for very sensitive measurements or long period widths,.

You get more information in chapter S2.4.6.2.3 and S3.4.11.4 of the Software Manual.

## 2. Special measurements

### 2.1 Capture measurements with fast pulse

Capture measurements will be also explained in chapter S3.3.6.1 of the Software Manual. The Fast pulse option will be described in chapter S6.5.2 and H2.2.

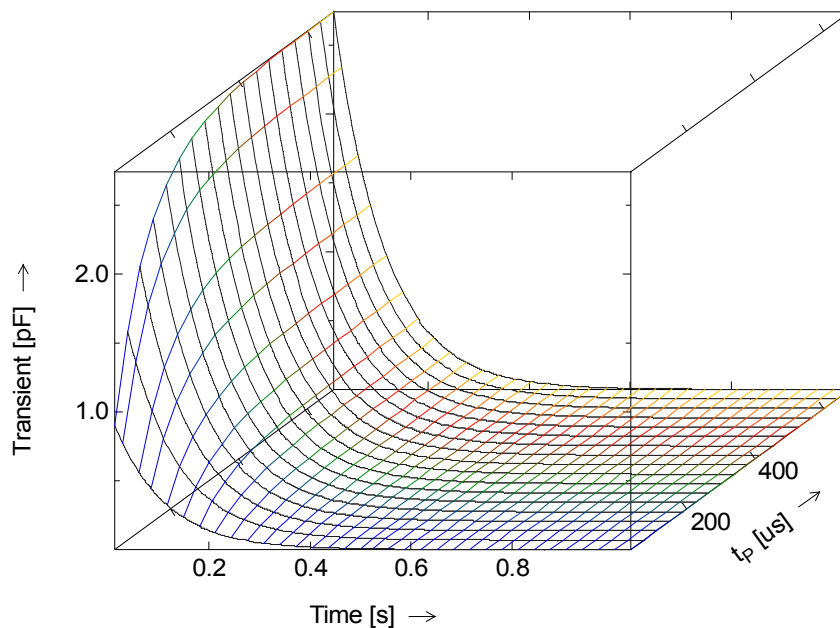
#### 2.1.1 Capture transient

The fast pulse interface with a fast pulse generator will be used to make DLTS tempscan or transient measurements with short and long pulse widths (20 ns until 10 ms). This gives the possibility of a level separation in the tempscan and of the direct measurement of the capture cross section.

Capture cross sections can be measured by variation of the pulse width. The trap level will not be completely filled at small pulse widths. The measured amplitude of the emission process depends on the pulse width. The pulse width then systematically incremented (linear) until the emission amplitude don't increment by the pulse width. The trap level is then completely occupied. The plot amplitude (or coefficient) of the measured emission transient versus pulse width yields to an exponential time curve which corresponds to the capture transient.

The next 3-dimensional plot demonstrates this type of capture measurement. The x/y-coordinates give the simulated emission transients in capacitance versus time. The 3rd dimension z-axis gives the varied parameter, the pulse width. Looking at the y/z layer of this 3d plot, the capacitance transient start value (close to transient amplitude) versus the pulse width, it can be seen, how this start value increases with increasing pulse width due to a successively enlarged filling level of the traps. This y/z layer gives directly the capture transient constructed by the measured emission transients amplitude. The measurement of the very fast capture transient has been transferred to several measurements of quite slow emission transients.

This measurement is also an example for transient measurement under varied parameter. It shows very nicely the trick, how the normally very fast capture transient (capture time constant  $t_c = 1\text{ ns to }1000\text{ ns}$ ) can be measured.



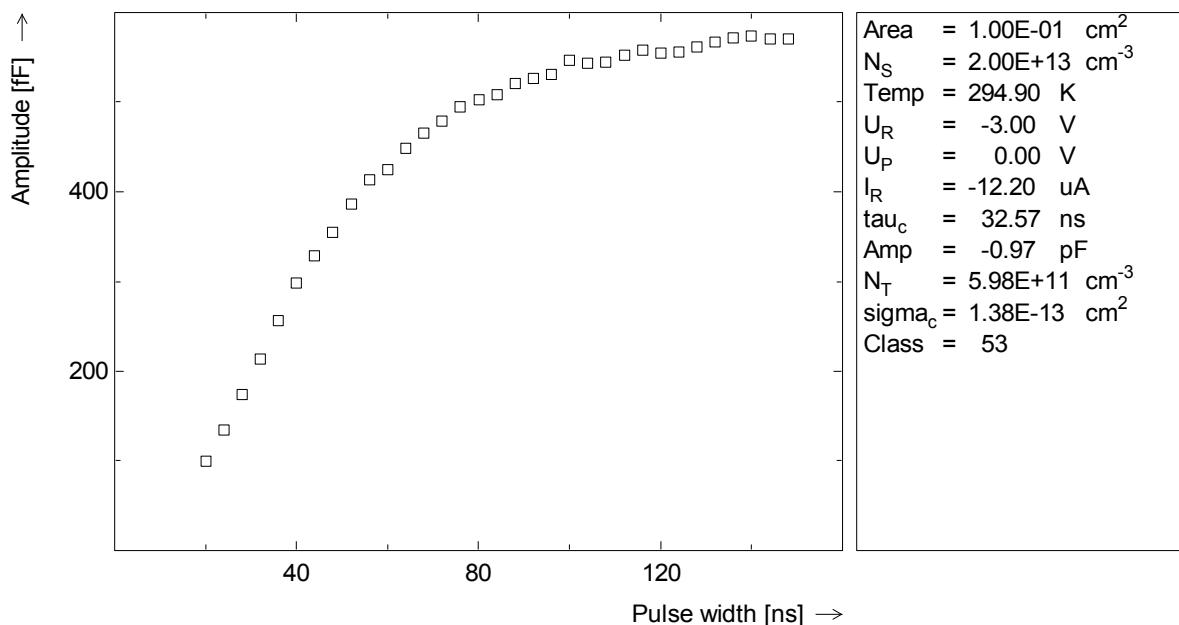
## 2.1.2 Calculation of capture time constant

There are some ways of obtaining the capture time constant:

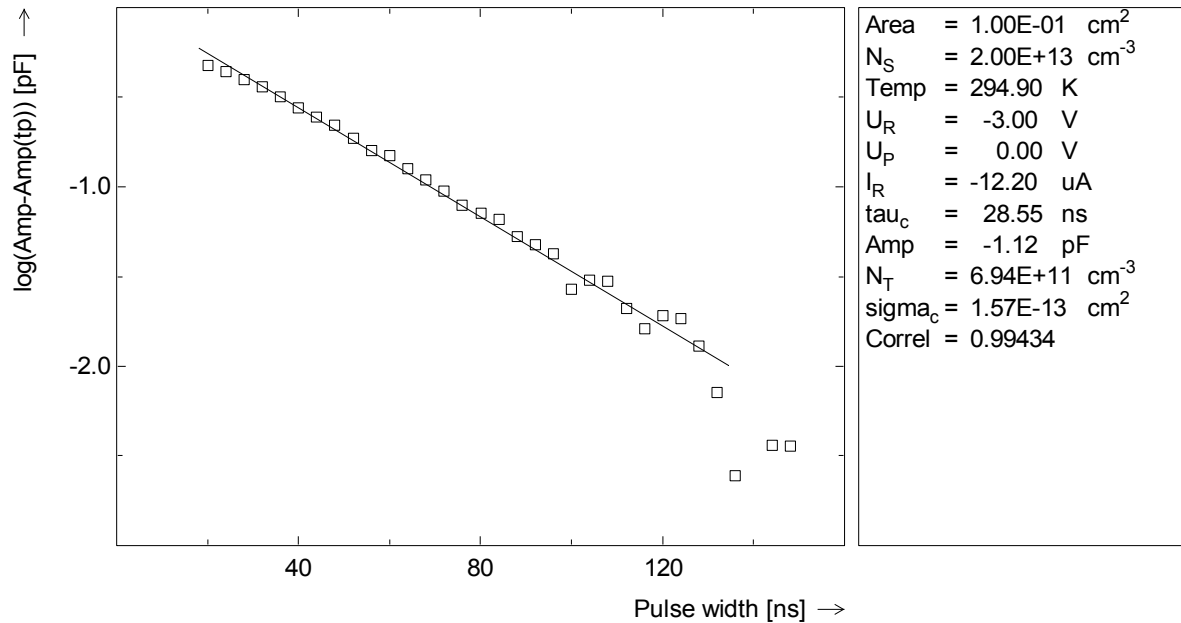
1. **Fourier transform:** The evaluation will be done by a direct analysis of the Fourier coefficients of the capture transient, see Theory Manual for the DLTFs technique.
2. **Linear regression:** The capture transient will be plotted in a logarithmic way and a linear regression yields to the results.
3. **HERA TranEval:** The HERA transient evaluation gives the results.
4. **Period scans, vertical plot:** The capture time constant can also be calculated by period scan with various pulse widths. This measurement needs a longer time, but here overlapping of traps can be observed. A vertical plot which shows the coefficients at a defined emission time constant yields again to the capture transient. This transient can then be evaluated by method 1 until 3.
5. **Period scans, maximum analysis:** The measurement will be done as at method 4. A maximum analysis allows the x/y-definition for every curve. As result you get also the capture transient.

All methods construct the capture transient as in the previous chapter described. For this are the Fourier coefficients or the amplitudes of the emission transients necessary. The emission amplitude will be calculated by the DLTFs technique.

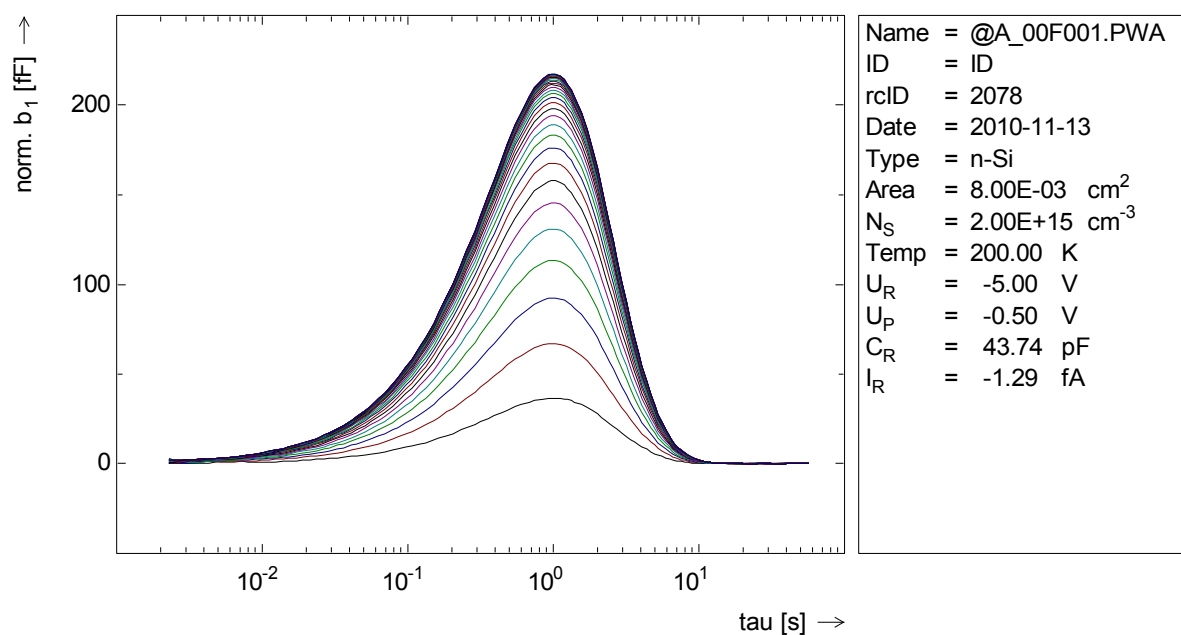
The next picture shows the constructed capture transient using the amplitude. The direct analysis (method 1) gives then the values for  $t_c$ ,  $A_c$  (capture time constant and amplitude) from which  $s_c$  and  $N_T$  are calculated. The measurements were done with a fast pulse generator.



The next picture shows the capture transient above by the second method. The y-axis is now the logarithmic amplitude. The slope of the linear regression gives also  $t_c$  and then  $s_c$ . In detail, the y-axis is not only the pulse width depending amplitude but also subtracted by the saturation amplitude. The disadvantage of this method is that the measurement must go to saturation (Amp). This is not always possible, especially because the Edge layer effect.



The following picture shows a simulation at pulse widths from 1 us until 33 us. Each curve represents a period width scan. The smallest peak refers to the smallest pulse width. A vertical plot at a defined emission time constant (vertical line) yields to the capture transient. Another possibility is the maximum analysis.



### 2.1.3 Determination of capture cross section

The capture cross section  $s_c$  can be calculated from the time constant  $t_c$  of this capture transient by  $t_c = (s_c \cdot v_{Th} \cdot N_s)^{-1}$ .

As discussed above, the measurement uses the fact, that a trap level is only partly filled, if the filling pulse width  $t_p$  is small enough compared with the capture time constant  $t_e$  of this level. The concentration of the captured carriers is detected by the normal emission transient, using the amplitude or a DC value. The capture time constant depends mainly on the capture cross section, the desired measurement result, and the shallow doping  $N_s$  (chapter T1.3 of Theory Manual). For that, not every capture cross section  $s_{n,p}$  can be measured in every sample because the fastest pulse is limited to 10ns. Large  $s_{n,p}$  ( $s_{n,p} > 1e-14 \text{ cm}^2$ ) can only be determined in low doped samples ( $N_s < 1e15 \text{ cm}^{-3}$ ). As a hint for the start value of the pulse width (for Silicon) the following approximation can be used:  $t_p(\text{start}) = 10\text{ns}/(s_{n,p} \cdot N_s)$ , with  $t_p$  minimum = 10ns better 20ns. It's an experience that smaller pulse widths, even if the pulse generator can supply it, does not completely reach the sample through standard BNC cables, see chapter H2.2 of the Hardware Manual. For the example below:  $s_{n,p} = \text{app. } 1e-13 \text{ cm}^2$ ,  $N_s = \text{app. } 1e13 \text{ cm}^{-3}$  give  $t_p(\text{start}) = 20\text{ns}$ .

For the selection of the largest pulse width that should be used for this measurement, a similar argumentation as for an optimized emission transient measurement can be used. Approximate 8 time constants, in this case capture time constants  $t_c$ , should be measured to get an optimized capture transient. A similar approximation as done for the  $t_p$  start value gives  $t_p(\text{End}) = 100\text{ns}/(s_{n,p} \cdot N_s)$ . For this estimation as a value for  $s_{n,p}$  the result of an Arrhenius plot from a tempscan measurement can be used although the evaluated values for the capture cross section from an Arrhenius plot and from this direct measurement differ due to the entropic factor  $X_{n,p}$  (see DLTS Theory Manual).

### 2.1.4 Isothermal parameter variation

In a similar way as shown above for the measurement and evaluation of the capture cross section the depths profile and field dependance measurements and evaluations are done. The software automatically supports only that evaluations, that is possible for the measured data. All evaluation given in standard literature are implemented and can be selected in the software.



### **3. Sample and measurement setups**

This chapter describes sample and measurement setups for special samples and measurements. It is not for all such samples valid. It should give you a help how to work with similar samples. A complete description of the software will be given in the Software Manual.

In the following means 'Sample setup' how to connect the sample and how to check it for good contact and so on. This includes the sample parameters and the base measurements as 'Test of contact' and simple 'C/V curve'.

'Measurement setup' means a full measurement like a tempscan or period scan.

If there is no hint in the following chapters then only the sample setup will be explained.

### 3.1 pnp/npn power devices

1. Fix sample to cryostat. Decide use of 100V options or not if available. If you want to use the 100V option, connect it and restart the software. Select there 'Use 100V' as described in chapter S6.5.1.
2. n-type should region be detected for irradiation defects, so connect for npn: device bias high to base and bias low to collector, or for pnp: bias to emitter and bias low to base.
3. If p-type region should be detected, use opposite connections.
4. Before connections
  - use/start: **New sample** → Test of contact (in any measurement menu)
  - use:  $U_R=0V$ , capacitance, as parameters
  - observe: capacitance reading on screen

**The capacitance should be quite high app. 500pF**

If connections are done and the capacitance reading is stable in the range of 1% go on. If not go to 1 and check connections to the sample.
5. Follow new sample program.  
Check polarity, C/V. C/V should be measured up to the desired reverse bias voltage. **Decide for your reverse bias voltage for the measurement and define it** in the software (new reverse bias). It may be changed again afterward.
6. Continue with new sample program.  
CR and CP is measured, the **minimum ranges for the C(V) and C(t) measurements are defined.**  
(Standards: **range 3 for static, range 2 for transient** measurement)
7. Continue with new sample program.  
CR is compensated. Check that it is done correctly. The difference between direct and compensated measurement should be below **1% or 1pF**. If not go to 1 or use I/V and C/V measurements to find the reason and restart 'new sample' program.
8. Continue with new sample program.  
Define the sample parameters. Sample ID (for automatic saving), area for correct calculations), and doping is important. The doping is also measured after the inputs by a C/V curve and a  $C^{-2}$  versus V evaluation. Make sure that it is transferred into the sample parameters.
9. When the C/V is done and the doping ( $N_s$ ) is defined, the sample is prepared for transients and tempscan measurements.
10. In any case do a transient measurement with the defined reverse bias voltage and pulse voltage to check the transient measurements. Afterward a tempscan can be setup. It is helpful to use the same parameters for this transient measurements as meant to do one tempscan measurement file.

If you have to restart the software or you want to change some conditions, use test of contact to ensure the minimum ranges are set properly, or use measurement parameter to set the minimum ranges to 3 and 2.

## 3.2 pnp/npn transistors

1. Fix sample to cryostat. Be careful to contact very accurate. The capacitances are very low, so do not use additional very long cables.
2. n-type should region be detected for irradiation defects, so connect for npn: device bias high to base and bias low to collector, or for pnp: bias to emitter and bias low to base.
3. If p-type region should be detected, use opposite connections.
4. Before connections
  - use/start: **New sample** → Test of contact (in any measurement menu)
  - use:  $U_R=0V$ , capacitance, as parameters
  - observe: capacitance reading on screen

**capacitance is quite low app. 2pF to 5pF**

If connections are done and the capacitance reading is stable in the range of **10%** go on. If not go to 1 and check connections to the sample.
5. Follow new sample program.  
Check polarity, C/V. C/V should be measured up to the desired reverse bias voltage. **Decide for your reverse bias voltage for the measurement and define it** in the software (new reverse bias). It may be changed again afterward.
6. Continue with new sample program.  
CR and CP is measured, the **minimum ranges for the C(V) and C(t) measurements are defined**.  
(Standards: **range 2 for static, range 1 for transient** measurement)
7. Continue with new sample program.  
CR is compensated. Check that it is done correctly. The difference between direct and compensated measurement should be below **10% or 1pF**. If not go to 1 or use I/V and C/V measurements to find the reason and restart 'new sample' program.
8. Continue with new sample program.  
Define the sample parameters. Sample ID (for automatic saving), area for correct calculations), and doping is important. The doping is also measured after the inputs by a C/V curve and a  $C^{-2}$  versus V evaluation. Make sure that it is transferred into the sample parameters.
9. When the C/V is done and the doping (Ns) is defined, the sample is prepared for transients and tempscan measurements.
10. **In any case** do a transient measurement with the defined reverse bias voltage and pulse voltage to check the transient measurements. Afterward a tempscan can be setup. It is helpful to use the same parameters for this transient measurements as meant to do one tempscan measurement file.

If you have to restart the software or you want to change some conditions, use test of contact to ensure the minimum ranges are set properly, or use measurement parameter to set the minimum ranges to 2 and 1.

### 3.3 FET

You find also a FET description in chapter S6.2.4 of the Software Manual.

1. Fix sample to cryostat. Be careful to contact very accurate. The capacitances are very low, so do not use additional very long cables.
2. Connect: **bias high to gate, bias low to source and AUX to drain.**
3. Use: measurement parameters/base: select DLTS mode 'current', AUX mode to 'SD FET' and disconnect bridge 'no'. This is for FET -I/V measurements  $I_{GS}$  versus V at different  $V_{DS}$ .
4. Before connections
  - use/start: „Test of contact“ (in any measurement menu)
  - use:  $U_R=0V$ , capacitance, as parameters
  - observe: capacitance reading on screen

If connections are done and the capacitance reading is stable in the range of **10%** go on. If not go to 1 and check connections to the sample.
5. Go to static program.
  - use: 'UDS' variation for measuring  $I_{GS}$  versus V at different  $V_{DS}$
  - define: Source Drain voltage range due to forward bias of the FET.  
Do not exceed 10mA forward bias current. Remind setting the current limit.
  - define: Gate Source voltage due to measure a complete I/V curve from reverse to forward bias voltage.
  - observe:  $I_{GS}$  versus V and decide for a reverse bias voltage (no current) and a pulse voltage (some current).
6. Decide to use capacitance DLTS (Gate Source capacitance) or current DLTS (Source Drain current after gate pulse).
  - C-DLTS:** change measurement parameters/base: select DLTS mode 'capacitance', AUX mode to 'auxiliary voltage',  
use check for contact etc. for min. range settings and compensating.  
(Standards: **range 2 for static, range 1 for transient** measurement)
  - I-DLTS:** leave measurement parameters unchanged.  
Remind: I-range 0 is the most sensitive one, but does have an additional recovery time constant of 1 ms.
7. Define the sample parameters. Sample ID (for automatic saving), area for correct calculations), and doping is important. In case of capacitance DLTS a C/V can be done and the doping ( $N_s$ ) can be defined, then the sample is prepared for transients and tempscan measurements.
8. **In any case** do a transient measurement with the defined reverse bias voltage and pulse voltage to check the transient measurements. Afterward a tempscan can be setup. It is helpful to use the same parameters for this transient measurements as meant to do one tempscan measurement file.

If you have to restart the software or you want to change some conditions, use test of contact to ensure the minimum ranges are set properly, or use measurement parameter to set the minimum ranges to 2 and 1.

### 3.4 MOS

You find also a MOS description in chapter S6.3 of the Software Manual.

1. Fix sample to cryostat. Be careful to contact very accurate, the MOS contact is very sensitive to pressure (can be damaged easily).
2. Connect: **bias high to gate, bias low to source.**
3. Use: measurement parameters/base: select DLTS mode 'Capacitance', AUX mode to 'no'.
4. Before connections
  - use/start: „Test of contact“ (in any measurement menu)
  - use:  $U_R=0V$ , capacitance, as parameters
  - observe: capacitance reading on screen

If connections are done and the capacitance reading is stable in the range of **10%** go on. If not also go on, but keep this in your mind for further measurements. On MOS there are memory effects possible that can cause a variation of the capacitance for a long time.
5. **Define the sample parameters.**
  - Change: Sample type to 'MOS'
  - define: **Oxide capacitance** (needed for all evaluations), **sample ID** (for automatic saving), **area** for correct calculations), and **doping** is important.
  - A C/V can be done afterward and the doping (Ns) can be defined.
6. Use: **static program**,
  - use: **HF C/V** measurements first
  - define: voltage range, begin with -1V to 1V,
    1. start measurement
  - observe: C/V behavior.
    - Check: do you see an inversion capacitance range? If yes go to 2
    - Check: are there **negative** values of the capacitance then **stop**.
      - The current might be too high and the diode is only a resistor. Check with an I/V measurement (same parameters as for the C/V). If the **current is higher** than **0,1 mA** use a new sample.
    - Check: Is there a capacitance change with voltage.
      - If no:** use higher, but symmetric voltage and go to 1. Be careful not to break electrically the oxide.
      - If yes:** use same voltage at the highest capacitance and change the voltage to lower capacitance (maybe 2V or -2 V) go to 1.
  - 2. Start Ns measurement.
    - Define voltage range: It should cover the accumulation (highest capacitance) and inversion (lowest capacitance) range of the diode.
    - Start C/V measurement.
    - Calculate Ns (evaluation/standard evaluation),
    - Use Ns for the sample parameters.
    - There are several additional measurement possibilities that can be used. Try.

## 7. Transient measurements.

Two different kind of transient are expected, the surface- (oxide-) states emission transients and the minority carrier generation (inversion-) transients.

### Surface state transients:

These transients normally do have a logarithmic time law, not an exponential one. Only in few cases it gives an exponential time law (see literature). It is the sum of a lot of energy distributed (and locally distributed) states at the oxide surface or/and in the oxide (oxide states). The surface states normally can be filled in short times (0.1 ms), oxide states are filled in dependence of the time and need long times (above 100ms).

This gives following measurement conditions:

Close to the surface means, close to ACCUMULATION, the maximum of the C/V curve. If we define accumulation at -2 V (n-type the opposite) we use reverse bias voltage shortly after the capacitance starts to drop, let say to 10% of the accumulation capacitance, e.g. -0.5V. The pulse should be to accumulation voltage.

So we have :  $U_R = -0.5 \text{ V}$  ,  $U_P = -2 \text{ V}$  ,  $T_W$  app. 0.002s to 2 s

The transient amplitude is quite low, similar to that of traps.

The transient can be evaluated as:  $N_{SS}$  logarithmic

The result of one transient gives the surface states density  $N_{SS}$  in  $\text{cm}^{-2}$

The result from a tempscan gives the surface states density as a function of the energy,  $N_{SS}(E)$ .

### Inversion transient:

This transient does have a linear time law. It is a majority signal (big). The reverse bias voltage should be in deep depletion or inversion range. For this example +2V to +5 V. The timescale is quite long (seconds to several 100 s). It has to be measured as long (period width) until the increase slope is finished and turned into a constant capacitance.

The pulse should be to accumulation voltage.

So we have :  $U_R = 2 \text{ V}$  ,  $U_P = -2 \text{ V}$  ,  $T_W$  app. 0.2s to 50 s

The amplitude of the transient is quite high, app. 10% of the reverse bias capacitance. The transient is evaluated by 'Zerbst' and gives the minority carrier lifetime and similar values (see literature).

The inversion transient can only in a short range be measured in an automatic tempscan (temperature dependent) because the hold time is also temperature dependent and it runs out of the measured range if using always a fixed period width.

## 3.5 PICTS measurements of compensated GaAs

You find also a current DLTS description in chapter S6.2.2 of the Software Manual.

### 3.5.1 Sample setup

1. Fix sample to cryostat.  
**Disconnect capacitance meter** from DLTS electronics and **connect sample** (BNC connector at the cryostat) **directly** to the DLTS measurement electronics, 'Bias' to sample high, 'I' to sample low.
2. Change: **DLTS measurement mode** to '**current**' (in any measurement menu)  
use: measurement/meas. parameters/ Base modes – DLTS '**current**'  
Keep flag 'Disconnect bridge' **on**
3. Before or directly after sample connection  
use/start: **check measure** / contact test (or **the hammer** as a shortcut)  
(in any measurement menu)  
use:  $U_R=0V$ , **current** (should be the only choice)  
observe: current reading on screen  
**The current should be very low (several  $10^{-11}$  A)**  
**This is the current offset of the current to voltage converter and amplifier**

If the 0V current of the sample (resistance > 100M $\Omega$ ) is positive, please use positive bias voltage, if negative please use negative bias voltage. You avoid by this a change of the current sign during TSC or I-DLTS measurements.  
The current-amplifier offset can not be compensated by hardware components.

4. Continue **check measure** / contact test (next).  
The current is measured at two different voltages  $V_R$  and  $V_P$ ,  $I_R$  and  $I_P$  is measured (use: start), the **minimum ranges for the  $I(V)$  and  $I(t)$  measurements are defined** (use: next).  
(Standards: **range 3 for static, range 1 for transient** measurement)
5. change to '**static measurements**'  
Use: measure/ I/V curve (or short cut **RV**)  
decide: **Voltage range** and **no.'s of data points** for the I/V curve  
measure: **I/V curve**  
evaluate: resistance of the sample  
use: 'plot/resistance plot' for the resistance evaluation  
any option is useful, we recommend '**I/V**'  
decide: The **bias voltage** for the measurements you want to do from this I/V (resistance) curve. Remember topic 3.
6. Define the sample parameters.  
Use: **Tools/sample parameters** (or the **book** as a shortcut)  
**Sample ID** (for automatic saving), area for correct calculations), and doping have to be defined. The doping can **not** be measured by a C/V curve and a  $C^{-2}$  versus V evaluation.

7. Adjust Laser light to sample.

Use/start: check measure / contact test (or the hammer as a shortcut)  
(in any measurement menu)

use:  $U_R$ =your in 5. defined voltage, **current** (should be the only choice)

observe: current reading on screen

switch the laser diode to '**continuously on**'

**observe: the current reading during mechanically aligning the laser onto the sample.**

**Stop when a maximum in the light indicated current may have been reached.**

The sample as well as the excitation laser is now setup correctly and ready for use is transients-, tempscan-, and TSC measurements.

8. **In any case** do a **transient measurement** with the defined reverse bias voltage and optical pulse to check that it works with the designed parameters. Afterward a log. transient, tempscan, TSC or ITS measurement can be setup.

It is helpful to use the same parameters for this transient measurements as meant to do in one tempscan measurement file.

### 3.5.2 Measurement setup

#### Select measurement:

Several measurement possibilities are possible using the DLTS. All these measurements are using the same measurement but with different parameters.

This measurement is the **current  $I(t)$**  of the sample as a function of **time  $t$** , that is a current transient. **Current** means the current between the two Ohmic contacts of the sample.

In fact that there is no space charge region etc. the traps inside the sample material, means between the contacts, may not be filled electrically. Therefore optical excitations are used, the **Photon Induced Current Transient Spectroscopy, PICTS**.

The spectroscopy can be done either as:

1. Tempscan
2. Isothermal period width scan (ITS) at different temperatures
3. TSC, Thermal Stimulated Current

**Now you should decide for which measurement you, want to go for. We always suggest to start with a Tempscan if the sample is quite unknown.**

#### Set measurement parameters:

1. Tempscan only
2. Period width scan only
3. TSC only
4. All together (1. - 3.) in one temperature variation scan (if useful)



As suggested above we always prefer to do an single tempscan first, to see what may be in the sample. All explained inputs are similar to period width scan, TSC etc.

Following parameters have to be defined: **bias voltage** UR (see sample setup), pulse width **tP** of the optical pulse, the period width **Tw**, the temperature range **Tstart**, **Tend**, and measurement density **Tdelta** (temperature increment between two measurements).

**Bias voltage:** should be set to a low current reading e.g. 2V (p-type).

**Pulse width:** should be set to a total filling of the traps and saturation of the current during the pulse. e.g. 1s.

**Period width:** at least **two period width** files should be defined (if not using a very fast overview measurement). One should be quite **fast**, but not faster than the recovery time. Our standard for this is **Tw=20.48 ms** (20ms). Down to 5.0ms may be selectable.  
The value for the **slow** period width is limited by the value of temperature ramp and the stability of it. For heating rates up to **0.05 K/s** with high stability (no temperature oscillation) we recommend **2.048 s** (2 s). In **higher rates** (or temperature oscillation) we suggest a limitation to **Tw=512 ms** (0.5s).

**Minimum time tM:** The **minimum measurement time tM** (more exact the total measurement times) defines the measurement sensitivity. A transient will always as often be measured and averaged till this time has been reached. E.g. tM=2s, for Tw=20ms this means an average over 100 transients, for Tw=0.5s it means an average over 4 transients. For both measurements we get the same signal to noise ratio (sensitivity). This is why this value is important. We suggest a value of **2 s for standard sensitivity** and 20 s for very sensitive measurements. For more details look in chapter 1.3 and S3.2.1.1.

**Use:** Tempscan program/measure/Tempscan:

define: **Base**

files for constant period width **2**  
leave all other inputs unchanged

define: **Temp**

leave all other inputs unchanged

define: **Transi(ents)**

Save transient data change to **128**

define: **bias/pulse**

reverse bias (e.g.) **2 Volt**  
pulse width **1 second**  
param(eter)s

pulse mode **optical**  
wave length as useful if using the variable wave source  
intensity as useful if not leave it unchanged

leave all other inputs unchanged

define: **fix Tw**

file 1 change to Tw **2.048 E-2 s**  
file 2 change to Tw **2.048 E+0 s** or to **5.12 E-1 s**  
leave all other parameters unchanged

use: **O.K.** Next input window appears

define: Temperatures	
StartTemp e.g.	<b>80 K</b>
StopTemp e.g.	<b>450K</b>
deltaTemp	<b>2K (1K)</b>
step factor for delta temp	<b>...T&lt;150K</b>
define: cryo parameters	
ramp use	<b>linear, computer</b>
rate	<b>0,02 to 0.2 (! Tw)</b>
cryo times	<b>normal</b>
check: path/name of file	change if necessary

use: **Start**     The measurement starts with setting the temperature.  
Your choice: Start manually at the actual temperature or wait till the desired temperature has been reached and the measurement automatically starts.

Comments to **period width (ITS) measurements** and **log transient measurements**:  
It is necessary to **keep the temperature constant** during these measurements. Therefore we suggest following setups for the ramp (several sets are possible).

1. possibility:

define: <b>cryo parameters</b>	
ramp use	<b>linear, controller or computer</b>
rate	<b>0,05</b>
hold	<b>yes (controller)</b>
cryo times	<b>slow</b>

2. possibility:

define: <b>cryo parameters</b>	
ramp use	<b>boxcar</b>
cryo times	<b>slow</b>
define: <b>cryo input</b>	
waiting times	
minimum f. T-check	<b>20 to 50 s</b>
maximum f. T-check	<b>50 to 100 s</b>
	due to time till constant temperatures
leave all other inputs unchanged	

Depending on your cryo system it can be that the 2. possibility is the best for very long measurement at one temperature (max.  $T_w \geq 100s$ ). You find more information about this problem in chapter S3.4.1.4 and S2.4.6.2 of the Software Manual.

## 4. Sample preparation

Although DLTS measurements can most easily be made on complete device structures such as diodes or transistors, it is sometimes necessary or more convenient to use bulk material that has either not been processed or that has been extracted from a specific part of a process prior to complete device fabrication.

All capacitance DLTS measurements require a rectifying barrier. The quickest and, most convenient way to form this on bulk semiconductor material is to use a metal-semiconductor (Schottky) contact. An ohmic contact is also required. There are thus two stages to producing a test structure on a bulk semiconductor sample.

### 4.1 The ohmic contact

The ohmic contact needs to have low resistance so that most of the potential applied to the device appears across the Schottky barrier. For bulk samples the contact is most easily formed over a large area on the back of the sample, wafer or slice. However, for measurements on epitaxial layers which are often grown on semi-insulating substrates (GaAs), the ohmic contact will need to be on the front surface, and should be adjacent to the Schottky contacts. It is useful to form the ohmic contacts in two distinct areas so that a point-to-point resistance measurement can be used to check the contact quality.

The general principle of ohmic contact formation is to deposit an alloy onto the semiconductor. The major constituent of the alloy will form an eutectic with the semiconductor, while the second element, usually as a minor constituent, will dope the semiconductor in the appropriate way (for example, gold-antimony is used for n-type silicon).

The alloy is deposited by vacuum evaporation or sputtering and is then sintered in an inert atmosphere or vacuum. Prior to the formation of the contact, therefore, it is essential that the surface is clean and oxide free.

There is a large literature describing the technology of ohmic contacts on a wide variety of materials and most laboratories have established procedures for the semiconductors they use. However, as a guide, typical procedures for ohmic contact formation to Si and GaAs are given below.

Generally a large ohmic contact is formed to the back of the material.

A bad Ohmic contact with a high serial resistance give problems at the capacitance measurement. In the worst case you get an inverted slope of the transient, see chapter H4.1.1 and H5 of the Hardware Manual.

### 4.1.1 Silicon sample preparation

The **first step** is to degrease the sample with a series of solvents using an ultrasonic bath. All solvents and acids used should be of electronic grade, and tools, glassware etc should be as clean as possible. The solvents must be applied in the order: trichloroethane, acetone and methanol followed by thorough rinsing with de-ionized water. Clean in each solvent for 10 minutes.

The **second step** requires the removal of native oxide. This is achieved by 20 seconds immersion in concentrated hydrofluoric acid (**caution** because extremely dangerous!), quenching with methanol, and then three thorough rinses with methanol. The sample should then be stored under methanol until it is ready to be transferred to the evaporator. It is not usually necessary to etch Si, just to remove the oxide.

**Evaporation** of the alloy is usually carried out in a vacuum environment. Cut a clean piece of the sample and transfer it as rapidly as possible to the evaporator. The slice is best dried in a jet of dry nitrogen. It is convenient to mount the slice on a strip heater so that it may be heated slightly, to remove any traces of solvent and also to allow in-situ sintering, prior to evaporation.

The evaporant charge (Au-Sb for n-type silicon or Au-Ga for p-type) should be melted onto the previously outgassed tungsten spiral with the shutter in place.

Prior to evaporation, the wafer should be heated to approximately 150°C (a thermocouple attached to the strip heater will give a sufficiently good indication) and held at this temperature during deposition. The required film thickness is not critical and 500Å to 1000Å is typical.

The **sintering** can be done in-situ using a heater as suggested above. The Au-Si eutectic temperature is 375°C and it is easy to monitor the sintering process by noting the distinct change in the texture of the film as the eutectic is formed; heating can be stopped as soon as the reaction has spread over the complete surface.

A problem can arise if silicon diffuses through the metal film: exposure to air will then result in formation of an insulating oxide layer. If this occurs, it may be easily removed by a further HF acid dip followed by the deposition of an additional 1000Å of pure gold.

As an alternative to Au-Ga for p-type silicon, it is possible to use pure aluminum. The preparation and deposition procedure is the same as previously described, except that the sintering temperature is 550°C. On cooling, the silicon recrystallizes containing aluminum at the solubility limit appropriate to the recrystallization temperature (around 1%); this produces a p+ region under the contact. It is not necessary to go through the second HF acid dip.

#### 4.1.2 Gallium arsenide sample preparation

The sample should be degreased by an ultrasonic wash in the following solvents in the order: trichloroethylene, acetone, methanol and then de-ionized water.

It is usually necessary to etch the GaAs and it may be desirable to protect the front surface by waxing the slice face-down onto a glass slide. A suitable etchant is  $\text{H}_3\text{PO}_4\cdot\text{H}_2\text{O}_2$  (100vol): $\text{H}_2\text{O}$  in the ratio 3:1:50, for one minute at room temperature. The sample should then be thoroughly rinsed in de-ionized water.

Immediately prior to putting the slice into the evaporator it should be immersed in concentrated hydrochloric acid for 1 minute to remove any oxide. Rinse with de-ionized water and dry with nitrogen gas.

**Alloy evaporation:** The substrate should be mounted on a heater strip. Prior to and during evaporation, the substrate should be heated to around 150 ° C.

A suitable mixture for n-type Au-Ge eutectic formation is 88% Au, 12% Ge by weight. The evaporant can be easily prepared by melting a mixture of the appropriate weights of powdered Ge and short lengths of fine gold wire in a quartz boat at 600°C - 700°C in a furnace tube under dry forming gas. Evaporate around 500Å of Au-Ge and follow this by 1000Å – 2000Å of Au.

A suitable contact material for p-type GaAs is Au-Zn, which is most easily deposited from separate sources. First deposit 200Å - 300Å of gold, then around 500Å of zinc and finally a further 2000Å of gold.

**Contact sintering:** A similar arrangement is used for n-type and p-type materials. Simply sinter at 450°C for 2 minutes.

MBE-grown material will have a heavily reacted indium layer on the back surface (the In is used to mount the wafers to the sample block). This provides an adequate ohmic contact to conducting substrates of both n- and p-type.

## 4.2 Schottky contact

It is not necessary to produce an 'ideal' Schottky contact. The diode is held in reverse bias so it is important that leakage currents are kept low, preferably below 10 $\mu$ A. As a general guide, if it is possible to obtain a satisfactory C vs V plot (ie a straight line with gradient corresponding to the doping level and an intercept giving a reasonable barrier height) up to a given reverse bias, then the diode should be satisfactory for DLTS. The PhysTech DLTS system can measure leakage currents at any temperature. Another good test is to look at the ideality (n) of the diode; at room temperature the forward current should increase by an order of magnitude for each 60mV increase in forward bias. This corresponds to an n-value of 1. If the required change in forward bias is 90mV, then  $n=1.5$ . For Si and GaAs it should be possible to achieve  $n=1.02$ . An upper limit for satisfactory DLTS is  $n=2$ .

### 4.2.1 Contact formation to silicon

Substrate preparation is identical to that used for the ohmic contacts. It is most important that the slice is transferred rapidly into the evaporator, and it should again be heated to around 150°C to drive off adsorbed gas prior to evaporation.

For n-type silicon, gold is a suitable contacting metal. Take care when probing the contact to avoid making deep scratches.

Aluminum can be used for p-type material.

In both cases 1000Å - 2000Å is a typical film thickness. Evaporate through a mask with an array of around 1mm diameter holes. If the sample has a low doping concentration the diameter of the Schottky contacts may be larger.

### 4.2.2 Contact formation to gallium arsenide

For contacts to epitaxial material, it is generally sufficient to degrease the sample and then remove any surface oxide by a quick immersion in hydrochloric acid, followed by quenching in deionized water. The sample should then be dried and transferred immediately to the evaporator. Again the sample should be heated to around 150°C prior to evaporation.

Aluminum can be used for both p- and n-type GaAs (barrier on more heavily doped p-GaAs can be rather low). If the surface needs to be etched this can be done controllably with H<sub>3</sub>PO<sub>4</sub>:H<sub>2</sub>O<sub>2</sub>:H<sub>2</sub>O in the ratio 3:1:50, which gives an etch rate of around 0.2  $\mu$ m/min at room temperature. Again, any oxide should be removed with hydrochloric acid.

### 4.2.3 Contacts for MCTS

For MCTS measurement it is necessary to use a semi-transparent Schottky diode. This is most easily produced by mounting a glass slide adjacent to the sample and evaporating enough material to give around 50% transmission of light. It is necessary to evaporate a thick contact pad at one edge of the semi-transparent metallization so that probing does not pierce the film. Aluminum is not suitable for the thin film because it oxidizes rapidly.

### 4.3 Sample mounting

Depending on your cryostat it can be that the cryostat stage is not electrically isolated and therefore the sample must be mounted onto an insulating substrate prior to mounting in the cryostat. A suitable medium for this purpose is a thin layer of mica or a thin, 100mm ceramic slice as described below.

If the cryostat stage is isolated then the sample may be mounted directly onto the stage with silver paint.

Once the ohmic and Schottky contacts have been formed, the sample may be mounted onto a substrate. If mica is chosen (this is supplied in the start-up kit), use a scalpel or other sharp blade to lift off a very thin layer. The mica should not have any cracks or holes in it because these will allow the silver paint to make contact with the stage.

Start by painting a solid circle of silver paint onto the mica, taking care not to paint over the edge. Then take up some silver paint onto a brush, from the bottom of the bottle where the paint is generally thicker, and place a small amount in the center of the solid circle. Before this thick layer of paint dries, carefully place the back of the, sample onto the wet paint, taking care not to smudge paint over the edges of the sample. The paint should take a few minutes to dry, after which it will be ready to mount in the cryostat.

For a good thermal contact it can be necessary to use silver paint to mount the sample in the cryostat. Use here a thin, even layer of quick drying silver paint. The sample can easily be removed using acetone.

**Caution:** If Ga-In eutectic is used for sample mounting take care to clean the stage thoroughly after use because the stage is silver and it may be attacked by the Ga-In. Do not use silver epoxy or very thick layers of either paste or paint because the thermal lag between the stage and sample will increase.